DEPARTMENT OF THE ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY, CORPS OF ENGINEERS
HANOVER, NEW HAMPSHIRE 03755

December 11, 1984

Snow and Ice Branch

SUBJECT: Mechanical Properties of Multi-Year Sea Ice, Phase II

Dr. J. F. Dorris
Shell Development Company
P.O. Box 481
Houston, Texas 77001

Dear Jim:

Enclosed for your review and comment is a copy of the paper "The effect of sample orientation on the compressive strength of multi-year pressure ridge ice samples" by Richter-Menge and Cox. The paper has been submitted to the ASCE Arctic '85 Conference. Please provide your comments within 30 days so that they may be considered prior to journal publication.

Sincerely,

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CF: G.F.N. Cox (w/o enclosures)
C. E. Smith, MMS (w/enclosures)

THE EFFECT OF SAMPLE ORIENTATION ON THE COMPRESSIVE STRENGTH OF MULTI-YEAR PRESSURE RIDGE ICE SAMPLES

Jacqueline A. Richter-Menge[1] and Gordon F.N. Cox[2]

Abstract

Matched pairs of horizontal and vertical sea ice samples were taken from a multi-year pressure ridge in the Beaufort Sea. Each pair was tested in uniaxial constant strain-rate compression to evaluate the effect of sample orientation on the compressive strength. The results indicate that sample orientation must be considered in the interpretation of ridge compressive strength data.

Introduction

The horizontal force that can be imparted to a structure during the impact of a multi-year pressure ridge may be the critical design load for arctic offshore structures in exposed areas of the Beaufort and Chukchi Seas. As a basis for design, a significant amount of work has been done to define the unconfined compressive strength of multi-year ridge ice samples (2,3,5). The majority of these tests, however, have been performed on vertically cored ice samples.

To investigate the influence of ridge sample orientation on the compressive strength a series of tests was performed on matched horizontal and vertical sample pairs. All of the samples were taken from a single multi-year pressure ridge located in the Beaufort Sea just northwest of Prudhoe Bay, Alaska (3). The horizontal and vertical ice samples were obtained in close proximity to one another and grouped in pairs according to the sample depth as measured from the top of the ridge. Each pair was tested at a constant strain-rate and temperature. This paper presents the results of these compression tests and compares the variation in horizontal and vertical strength with respect to sample ice type, crystal orientation, porosity and grain size.

Coring Techniques

The vertically cored multi-year ridge samples were obtained using the CRREL 4-1/4-inch-diameter fiberglass coring auger (9). A 12-inch-diameter coring system was used as the first step in obtaining the horizontal samples. A 12-inch fiberglass coring auger was mounted on a specially modified gasoline post hole digger. Approximately 1 meter of core was augered and the core barrel was removed from the hole. A core retrieval system was then lowered into the hole to break and catch the core. Once the 12-inch-diameter ice core was retrieved, it

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was laid on its side. A drill press with a 4-1/4-inch-diameter hole saw was then used to obtain the horizontal samples (Fig. 1). Additional lengths of 12-inch-diameter core could be obtained down a particular hole by using extension rods with 12-inch-diameter spacers. A more detailed description of this coring system is given in Cox et al. (3).

Careful field notes were taken throughout the drilling process to document the location of each ice sample with respect to the top of the ridge. This information was later used to match the vertical and horizontal samples according to depth. The 4-1/4-inch-diameter (vertical samples) and the 12-inch-diameter (horizontal samples) holes drilled to obtain the matched pairs were located between 0.5 and 1 m apart along the top of ridge.

Test Methods

Twenty-two horizontal and 22 vertical ridge ice samples were combined according to the sample depth to give 20 matched pairs. All of the samples were tested in uniaxial compression at a constant strain-rate of 10^{-4} s^{-1}. Nineteen tests (nine pairs) were performed at -5°C and 25 tests (11 pairs) were completed at -20°C.

Dumbbell specimens were prepared from 10.7-cm-diameter cores. Samples were first rough-cut on a bandsaw, and the ends were milled square on a milling machine to produce a 25.4-cm-long test specimen. Synthane end caps were then bonded to the sample using fresh water to freeze them to the milled end planes. The end-capped samples were turned on a lathe to a dumbbell shape with a neck diameter of 10.2 cm. The form tool used to prepare the dumbbell compression specimens

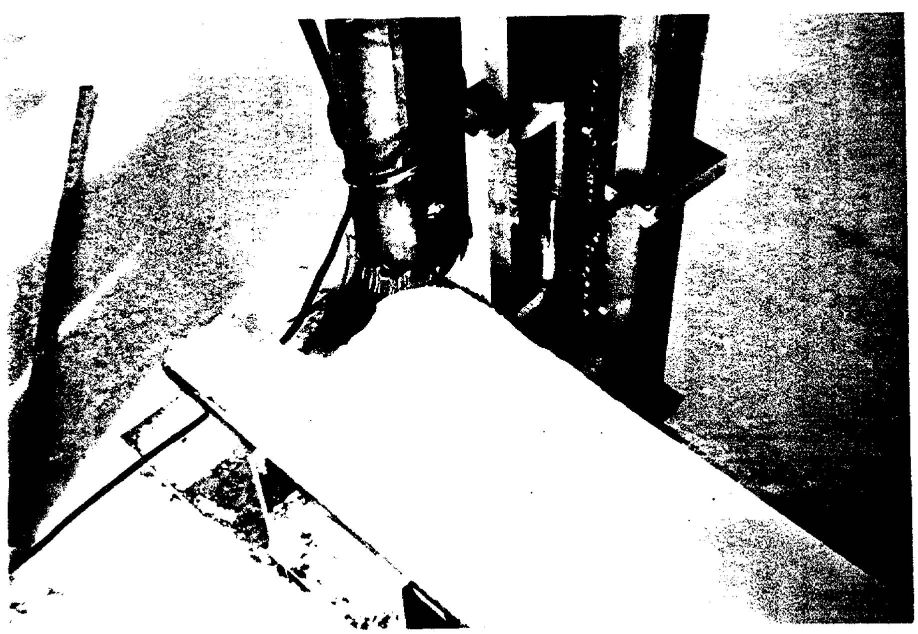


Figure 1. Drill press used to obtain 4-1/4-inch diameter horizontal samples from 12-inch-diameter vertical core.

had a radius of curvature of 20.4 cm, twice the diameter of the finished neck. This radius was chosen to minimize stress concentrations near the sample end planes. Every effort was made to produce properly sized, precision-machined test samples utilizing recommended methods (6,12).

All of the compression tests were performed on a closed-loop electrohydraulic testing machine. The machine had two actuators with capacities of 1.1 and 0.11 MN and a fast-response, high-flow-rate servo-valve. The load frame of the machine had a capacity of 2.2 MN. Strain-rates were controlled by monitoring the full sample strain with an extensometer, which was attached to the synthane end caps bonded to the test specimen (Fig. 2). Strains on the necks of the specimens were also monitored with a pair of DCDTs to provide accurate strain, strain-rate and modulus data. The tests were programmed to continue to 5% full sample strain to examine the post-yield behavior and residual strength of the ice. Since this resulted in considerable deformation of the test specimen, strain rates could not be controlled by the transducers mounted on the ice. Test temperatures were controlled to within 0.5°C by placing the sample in an environmental chamber mounted between the columns of the testing machine. The lower machine platen was also refrigerated to eliminate any thermal gradient problems. Load and sample strain-rate data were recorded on an XY

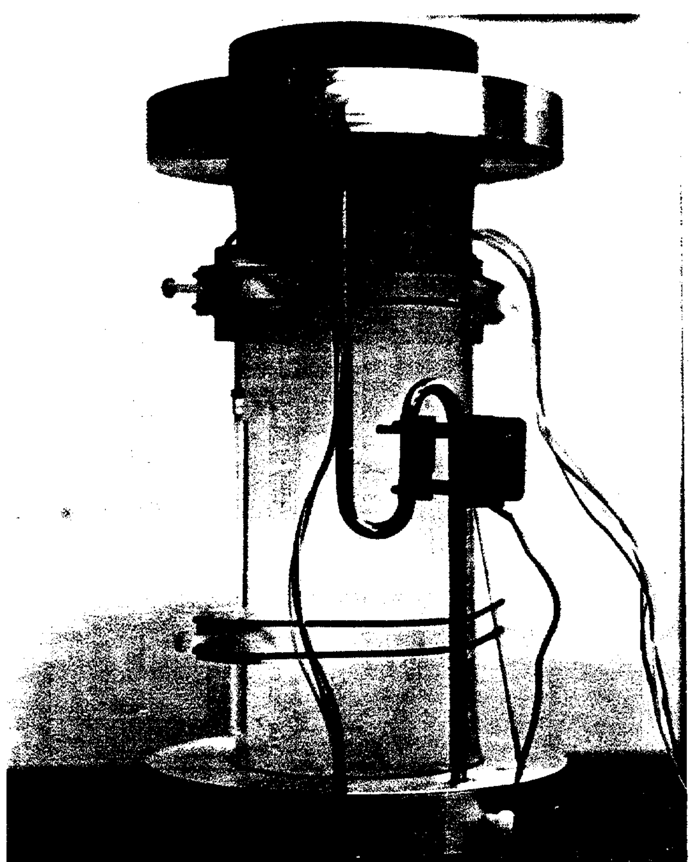


Figure 2. Instrumented uniaxial constant strain-rate compression test specimen.

plotter, a strip chart, and an FM magnetic tape recorder. Detailed information on our sample preparation and testing techniques can be found in Mellor et al. (2).

Ice Description

The matched horizontal/vertical pairs were taken from one multi-year pressure ridge. Each test specimen was classified according to the multi-year pressure ridge ice structural classification scheme proposed by Richter and Cox (10). This scheme divides the ice samples into three major ice texture categories: granular (I), columnar (II) or a mixture of columnar and granular (III). If a sample was designated as columnar or contained large fragments of columnar ice, the ice thin sections were analyzed on the Rigsby Universal Stage (7). These measurements provided us with information on the mean angle between the crystallographic c-axes and the load direction (σ:c) and the angle between the columns or direction of elongation of the crystals and the load direction (σ:z). We could also use the measurements to determine whether the crystallographic c-axes were directionally aligned or unaligned. The photographed thin sections of each sample helped to confirm the measurements. The granular ice in the thin section was not analyzed on the universal stage because the grain size was too fine, averaging 1 mm in diameter. The granular ice was observed and photographed between crossed polaroids and the crystals appeared to be randomly oriented.

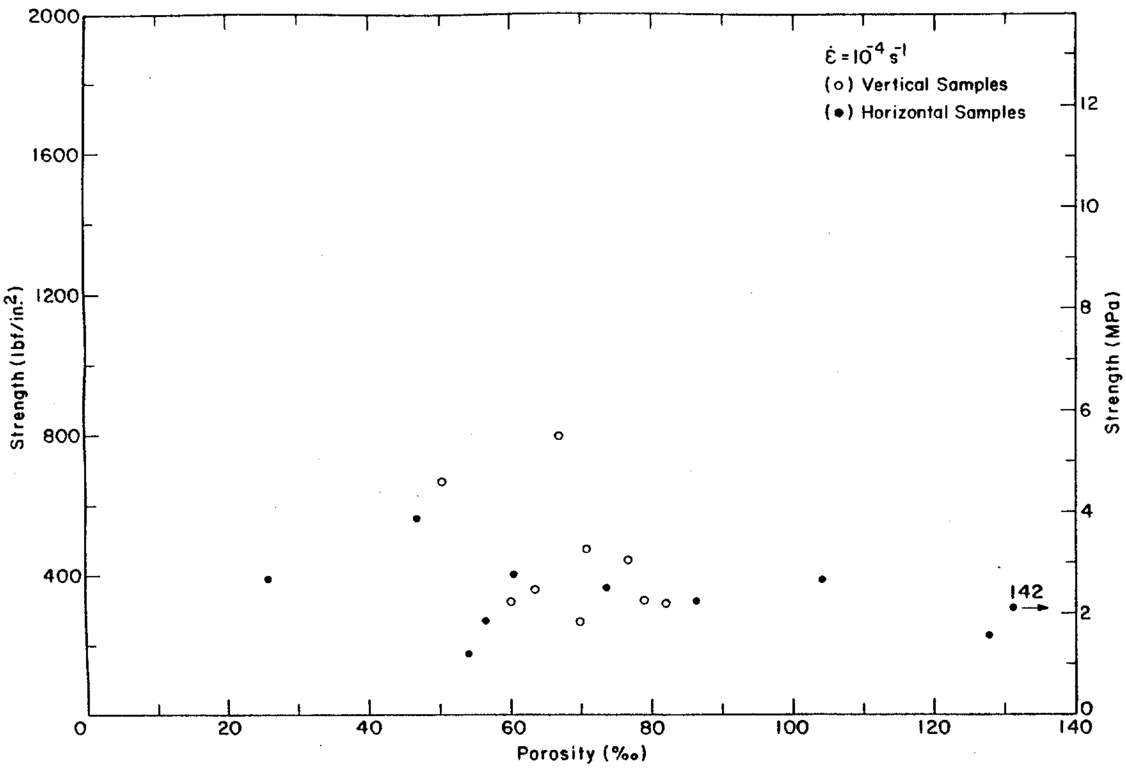
Ice porosities were also calculated from the salinity, density and temperature of each sample (4). The test specimens had an average salinity of $2.61 \pm 1.20^{o}/oo$ and an average density of 0.884 ± 0.029 Mg/m^3 at −20°C. Average grain sizes were estimated by using the ice thin section photographs. Each photograph contained a millimeter scale next to the thin section for grain size analysis.

Test Results and Discussion

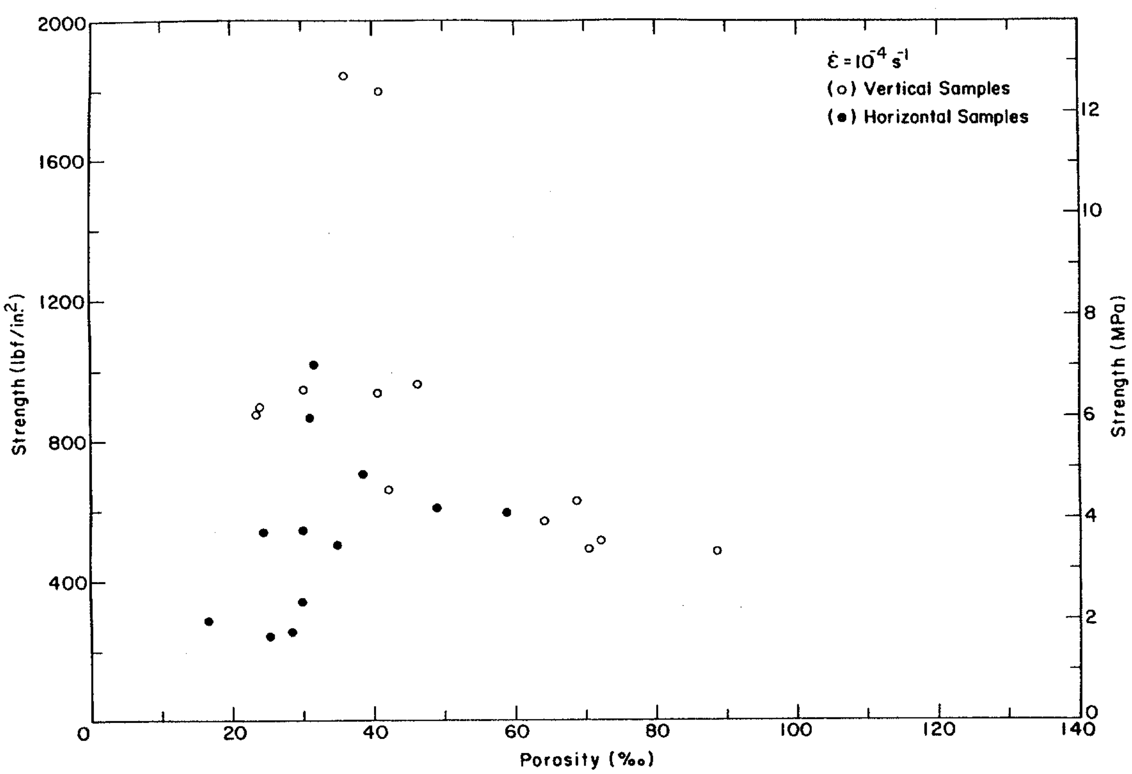
The uniaxial compressive strength of the paired samples is plotted against the ice porosity in Figure 3. The sample strength is defined as the maximum stress reached during the test. In general, the strength of the samples increased with a decrease in temperature. This same trend has been observed in earlier multi-year ridge sample tests done at different strain-rates and temperatures (1).

The strength, structure, grain size and porosity for each test specimen is given in Table 1. The horizontal (H) and vertical (V) samples are grouped according to pairs. One interesting thing to note is that, although the test samples were randomly selected, each test condition is dominated by one ice type. The majority of the samples tested at −5°C were mixed or brecciated ice, Type III. Brecciated ice is ice composed of columnar fragments in a granular matrix. The specimens at −20°C were mostly columnar, Type IIA.

Our observations on the structural variation of ice strength for the columnar samples tested at −20°C are in agreement with the findings of Peyton (8) and Wang (13). Columnar samples loaded parallel to the direction of elongation of the crystals and normal to



a. Test temperature -5°C.



b. Test temperature -20°C.

Figure 3. Uniaxial compressive strength versus porosity for horizontal and vertical samples tested at $10^{-4}\ s^{-1}$.

Table 1. Strength, structure and porosity of horizontal and vertical sample pairs tested at 10^{-4} s^{-1}.

a) Test temperature -5°C.

Sample No.	Strength (MPa)	Ice Type	Average Grain Size (mm)	Porosity (°/oo)
RC32-133/160V	2.28	IIIB		78.8
		50% Granular	Granular <1	
		50% Columnar		
RC43-150H	2.66	IIIB	≤1	104.0
		80% Granular		
RC33-205/232V	3.30	TYPE IIIB:		70.6
		Top II Aligned	Columnar 50x10	
		σ:z=0°, σ:c=90°		
		Middle I	≤1	
		Bottom IIA Unaligned	20x6	
		σ:z=20°		
RC43-222H	2.77	III		60.4
		70% Granular	≤1	
		30% Columnar		
RC46-047/073V	2.50	TYPE IIIB:		63.3
		Top-Middle IIIB		
		70% Granular		
		Bottom IIA Aligned	30x10	
		σ:z=8°, σ:c=82°		
RC44-073H	2.25	IIIA		86.2
		20% Granular	≤1	
		80% IIA Aligned	25x10	
		σ:z=86°, σ:c=82°		
RC44-060H	1.57	III		127.7
		60% IIA Aligned	28x7	
		σ:z=90°, σ:c=64°		
		40% IIIB		
RC46-083/110V	5.52	IIIA		66.7
		90% IIA Aligned	35x12	
		σ:z=4°, σ:c=86°		
		10% Granular	<1	
RC44-086H	2.69	IIA Aligned	30x10	25.8
		σ:z=85°, σ:c=90°		
RC46-147/173V	1.87	IIIB		
		85% IIA Aligned	30x8	69.7
		σ:z=15°, σ:c=80°		
RC44-156H	1.21	IIIA		54.0
		90% IIA Aligned	45x12	
		σ:z=78°, σ:c=30°		
RC46-246/272V	3.08	IIIA		76.5
		90% IIA Aligned	30x10	
		σ:z=8°, σ:c=82°		
RC44-265H	1.87	IIIB		56.4
		30% Granular	<1	
RC47-025/053V	2.22	TYPE IIIB:		81.8
		Top IIA Aligned	50x15	
		σ:z=0°, σ:z=90°		

Table 1 (cont'd).

		Middle I	<1	
		Bottom II Aligned	25x8	
		σ:z=0°, σ:c=90°		
RC45-040H	2.11	IIIA		42.2
		Vertical crack		
		90% IIA Aligned	22x10	
		σ:z=80°, σ:c=45°		
RC47-191/217V	4.61	IIIA		50.2
		90% IIA Aligned	35x10	
		σ:z=5°, σ:c=85°		
RC44-204H	3.87	IIIA		46.7
		90% IIA Aligned		
		σ:z=85°, σ:c=10°		
RC47-275/302V	2.25	IIA Unaligned	Top-Middle 20x15	59.9
		σ:z=20°	Bottom 18x8	
RC44-288H	2.52	IIIB		73.5
		50% Granular	<1	
		b) Test temperature -20°C		
RC32-231/258V	6.64	IIA Aligned	Columnar 30x15	46.2
		σ:z=15°, σ:c=76°		
RC43-245H	3.77	IIA Aligned	30x7	29.9
		σ:z=86°, σ:c=12°		
RC32-267/294V	4.56	IIA Aligned	42x20	42.1
		σ:z=15°, σ:c=80°		
RC33-268/295V	6.20	IIA Aligned	25x12	24.0
		σ:z=15°, σ:c=78°		
RC43-280H	4.88	IIA Aligned	30x10	38.5
		σ:z=90°, σ:c=5°		
RC32-303/328V	3.95	IIIB		64.1
		60% Granular	Granular <1	
		40% Columnar		
RC43-316H	2.36	IIA Aligned	60x20	29.8
		σ:z=85°, σ:c=25°		
RC32-343/396V	3.34	III		88.5
RC43-357H	4.12	IIIB		58.7
		60% Granular	<1	
		40% Columnar		
RC33-242/268V	6.53	IIA Aligned	45x15	30.1
		σ:z=10°, σ:c=82°		
RC43-257H	3.73	IIA Aligned	30x15	24.4
		σ:z=85°, σ:c=0°		
RC33-368/395V	6.47	III		40.6
RC43-381H	5.98	III		31.0
RC46-121/147V	3.57	IIIB		72.1
		50% Granular	<1	
RC44-128H	1.76	IIA Aligned	48x22	28.4
		σ:z=65°, σ:c=24°		

Table 1 (cont'd).

RC46-173/199V	3.40	IIIB 60% Granular	<1	70.4
RC44-186H	7.02	IIA Aligned σ:z=0°, σ:c=90°	50x18	31.6
RC46-276/303V	4.34	IIIB 60% Granular	<1	68.7
RC44-299H	4.20	IIIB 70% Granular	<1	48.9
RC47-090/116V	12.40	IIA Aligned σ:z=0°, σ:c=90°	35x10	41.0
RC44-103H	3.48	IIA Aligned σ:z=90°, σ:c=20°	40x12	34.8
RC44-116H	1.68	IIA Aligned σ:z=90°, σ:c=25°	40x12	25.3
RC47-127/153V	12.73	IIA Aligned σ:z=3°, σ:c=87°	45x10	36.0
RC44-141H	1.98	IIA Aligned σ:z=90°, σ:c=35°	45x12	16.6
RC47-302/329V	6.03	TYPE III: Top III Middle-Bottom IIA Aligned σ:z=10°, σ:c=80°	65x20	23.5

the crystal c-axes (σ:z=0°, σ:c=90°) were extremely strong. Specimens loaded perpendicular to the direction of crystal elongation and parallel or normal to the c-axes (σ:z=90°, σ:c=0° or 90°) had a significantly lower strength value. As the angle between the crystal c-axes and the applied load approached 45° in these columnar samples, the strength decreased further. The compressive strength of the mixed and granular ice samples tested at −20°C was comparable to the strength of columnar samples loaded with σ:z=90° and σ:c=0° or 90°.

The majority of the mixed ice samples tested at −5°C contained large columnar fragments. Results of the compression tests indicated that the orientation of the large columnar fragments within the sample had an influence on the strength value. If the columnar ice fragments in the sample were oriented with the direction of crystal elongation parallel to the load, the sample failed at a relatively high load (comparable to the strength of σ:z=90°, σ:c=0° loading in a columnar sample). Deformation in these samples occurred in the granular material surrounding the columnar fragments. As the angle between the direction of crystal elongation and the load approached 45°, the strength of the mixed ice decreased and the majority of sample deformation took place in the columnar fragments.

The difference in the compressive strength between horizontal and vertical pairs was found to depend on the ice structure. In general, the vertical samples had a higher strength value. At −5°C the mean compressive strength of the vertical samples was 30% higher (Table 2). At −20°C the average strength of the vertical and horizontal

Table 2. Summary of compressive strength data for the horizontal and vertical samples.

	Uniaxial Compressive Strength								
	Maximum		Minimum		Mean		Mean Porosity		
	(MPa)	($lbf/in.^2$)	(MPa)	($lbf/in.^2$)	(MPa)	($lbf/in.^2$)	(ppt)	Samples
-5°C (23°F)								
10^{-4} s^{-1} V	5.52	800	1.87	271	3.07±1.23	445±179	69	9
10^{-4} s^{-1} H	3.87	561	1.21	175	2.35±0.74	341±108	78	10
10^{-4} s^{-1} all	5.52	800	1.21	175	2.69±1.04	390±151	73	19
-20°C (-4°F)								
10^{-4} s^{-1} V	12.73	1846	3.34	485	6.17±3.10	894±450	50	13
10^{-4} s^{-1} H	7.02	1018	1.68	243	3.74±1.67	543±242	33	12
10^{-4} s^{-1} all	12.73	1846	1.68	243	5.00±2.70	725±392	42	25

H - Horizontal
V - Vertical

samples differed by 65%. The most significant differences in strength occurred in sample pairs of columnar ice.

The σ:z angle measurement from the vertical columnar samples at both -5 and -20°C varied between 0 and 20°. The horizontal columnar samples had a σ:z measurement that ranged from 90 to 0°; however, 80% of these measurements were greater than or equal to 85°. This indicates that many of the columnar ice blocks incorporated into the multi-year ridge during its formation lie in a near horizontal position. The same observation has been made in columnar ridge ice samples taken from ten additional Beaufort Sea multi-year pressure ridges (11). In this position the large columnar blocks are most stable. As a result of this apparent preferential block orientation, the majority of vertically cored columnar ridge test specimens are loaded nearly parallel to the direction of crystal elongation (σ:z=0°). This is the hard fail direction in columnar ice. Horizontal columnar samples tend to have an angle of 90° between the long columns and the applied compressive load, giving a lower strength. Work by Peyton (8) has shown that the strength values can differ between these two loading conditions by as much as a factor of three, depending on the σ:c angle. Note in Table 2 that the greatest variation between the horizontal and vertical mean compressive strength occurs at -20°C where there were a larger number of columnar pairs.

In general, sample pairs of mixed and granular ice had comparable compressive strength values. Some vertical samples tended to have a slightly higher strength. This may reflect the influence of internal columnar fragment orientation as discussed earlier. As in the columnar samples, the σ:z measurements from the mixed samples indicated that the direction of elongation of the crystals was nearly vertical in most cases. At both -5 and -20°C these samples showed a decrease in strength with an increase in ice porosity. This same trend was also noted in the earlier work by Cox et al. (1).

There was no apparent influence of grain size on the compressive strength in a given ice texture category.

Conclusions

The compressive strength of multi-year pressure ridge ice samples is affected by sample orientation. This influence can be explained by sample ice structure. As described in earlier work by Richter-Menge and Cox (11), crystallographic measurements made on columnar ridge ice samples indicate that most of the large columnar blocks in a compression ridge lie in a near-horizontal position. In this orientation the direction of elongation of the crystals or the columns is near vertical. Vertical columnar samples taken from the preferentially oriented internal blocks have a compressive strength 2-3 times higher than a horizontal columnar sample. This directional characteristic may give a mean compressive strength value that is higher when obtained from vertical samples. The variation will depend on the number of columnar test specimens and their crystallographic c-axis orientation since the compressive strength of granular ridge ice samples is isotropic.

The presence of preferentially oriented columnar ice blocks may also affect the large scale mechanical properties of multi-year pressure ridges. If a ridge contains a significant number of columnar blocks of ice in which the direction of crystal elongation is vertical we might expect the overall strength of the ridge to be lower in the horizontal direction than in the vertical direction.

The results of this paper and our earlier work are by no means conclusive. They do imply, however, that more field work needs to be done to characterize the internal structure of multi-year pressure ridges. Better definition of the ridge characteristics will aid in the application of test results to actual loading cases and in the design of reliable ridge models.

Acknowledgments

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References

1. Cox, G.F.N., Richter, J.A., Weeks, W.F. and Mellor, M. "A summary of the strength and modulus of ice samples from multi-year pressure ridges," Proceedings, Third International Offshore Mechanics and Arctic Engineering Symposium, New Orleans, vol. 3, pp. 126-133, 1984.

2. Cox, G.F.N., Richter-Menge, J.A., Weeks, W.F., Mellor, M. and Bosworth, H. "Mechanical properties of multi-year sea ice, Phase I: Test results," U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report 84-9, 105 p., 1984.

3. Cox, G.F.N., Richter-Menge, J.A., Weeks, W.F., Mellor, M., Bosworth, H., Durell, G. and Perron, N. "Mechanical properties of multi-year sea ice, Phase II: Test results," U.S. Army Cold Regions Research and Engineering Laboratory, CRREL Report, in press.

4. Cox, G.F.N. and Weeks, W.F. "Equations for determining the gas and brine volume in sea ice samples," Journal of Glaciology, vol. 29, no. 2, pp. 306-316, 1983.

5. Frederking, R.M.W. and Timco, G.W. "Mid-winter mechanical properties of ice in the southern Beaufort Sea," Proceedings, Sixth International Conference on Port and Ocean Engineering under Arctic Conditions (POAC '81), Quebec City, Canada, 27-31 July 1981, vol. 1, pp. 225-234.

6. Hawkes, I. and Mellor, M. "Deformation and fracture of ice under uniaxial stress," Journal of Glaciology, vol. 11, no. 61, pp. 103-131, 1972.

7. Langway, C.C. "Ice fabrics and the universal stage," SIPRE Technical Report 62, 1958.

8. Peyton, H.R. "Sea ice strength," Geophysical Institute, University of Alaska, Report UAG-182, 1966.

9. Rand, J.H. "The CRREL four-inch ice coring auger," U.S. Army Cold Regions Research and Engineering Laboratory, report in preparation.

10. Richter, J.A. and Cox, G.F.N. "A preliminary examination of the effect of structure on the strength of ice samples from multi-year pressure ridges," Proceedings, Third International Offshore Mechanics and Arctic Engineering Symposium, New Orleans, vol. 3, pp. 140-144, 1984.

11. Richter-Menge, J.A. and Cox, G.F.N. "Structure, salinity and density of multi-year sea ice pressure ridges," Proceedings, Fourth International Offshore Mechanics and Arctic Engineering Symposium, Dallas, 17-22 February, 1985.

12. Schwarz, J., Frederking, R., Gavrillo, V., Petrov, I.G., Hirayama, K.I., Mellor, M., Tryde, P. and Vaudrey, K.D. "Standardized testing methods for measuring mechanical properties of ice," Cold Regions Science and Technology, vol. 4, pp. 245-253, 1981.

13. Wang, Y.S. "Crystallographic studies and strength tests of field ice in the Alaskan Beaufort Sea." Proceedings, Fifth International Conference on Port and Ocean Engineering under Arctic Conditions (POAC '79), Trondheim, Norway, vol. 1, pp. 651-665, 1979.